

# GEOTHERMAL ENERGY IN A SUSTAINABLE BUILT ENVIRONMENT

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**Abstract:** Geothermal energy is usually perceived to be about gushing geysers and bubbling mud pools and limited to only the small volcanically active parts of the Earth's surface. Nothing could be further from the truth. Geothermal energy is in fact an incredible store of energy found in all parts of the world which is beginning to be understood and used for our sustainable future. There are two basic forms of this energy. One form (sometimes referred to as hot dry rocks or enhanced geothermal systems), makes use of the heat ( $>200^{\circ}\text{C}$ ) in the rocks at depths of up to about 5 kms to produce electricity from extracted (but returnable) hot water. There are several locations around the world where "proof of concept" stage has been or about to be reached suggesting that within the next few years, these systems may be providing a significant proportion of our base-load electricity. The other form makes use of the heat (and the cooling potential) of the soils and rocks within the upper few tens of metres from the surface to heat and cool buildings. It involves the circulation of a fluid through pipes built into building foundations or in specifically drilled boreholes, and back to the surface where heat stored in the fluid is extracted by a heat pump, and used to heat a building. The cooled fluid is reinjected into the ground loops to heat up again to complete the cycle. In cooling mode, the system is reversed with heat taken out of the building transferred to the fluid which is injected underground to dump the extra heat to the ground. The cooled fluid then returns to the heat pump to receive more heat. There are many thousands of these systems installed around the world but many countries have been slow to pick up on their enormous potential. The paper explains how these systems work and looks at some of the issues which require attention in the near future for geothermal energy to become a truly sustainable, renewable and most importantly, continuous, energy source.

**Keywords:** geothermal energy, hot dry rocks, enhanced geothermal systems, direct geothermal heating and cooling, ground source heat pumps

## 1 Introduction

Geothermal energy is the heat energy that is stored in the Earth's crust. The three primary sources of this energy are the heat transferred from our planet's core of molten metal, the heat generated by the decay of naturally occurring radioactive materials, and the heat collected through the ground surface from the sun's radiant energy.

There have been many estimates made of what total quantity of heat energy is present in the Earth's crust and how much of this may be available for extraction. One such estimate is that the total heat available within the upper 5 kms of the Earth's surface is about  $140 \times 10^6$  EJ (WEC 1998). If only 1% of this could be used at the current rate of world energy consumption of about 500 EJ/year, this would provide the world with all its energy for 2,800 years. However, it must be recognised that this energy is also being replaced by heat from the various sources given above. According to Bertani (2010), this amount is of the order of about 660 EJ/year, suggesting that even if we were able to provide all our power requirements from geothermal energy, it would still be fully sustainable.

Humans have made use of geothermal energy since prehistoric times with thermal pools and hot springs ("hydrothermal" energy) being used for heating, cooking, bathing and therapeutic purposes. The first district heating system was introduced to the central French town of Chaudes-Aigues in the 14<sup>th</sup> century. There are many other modern examples of this application around the world where hot

water taken from depths of up to about 1 km is piped to heat a wide range of domestic, commercial and industrial buildings and other infrastructure. Although electricity was first generated using steam from a geyser in Italy in 1904, it was not until 1958 that New Zealand started commercial power generation using separated steam. This form of power generation is now common in many countries with hydrothermal resources close to the ground surface.

It would be fair to observe that the use of geothermal energy up until relatively recently is associated with areas where ground temperatures are generally in excess of what would be the normal range under the majority of the Earth's surface. These areas are mostly linked with the regions of volcanic activity that are found at tectonic plate boundaries. While these limited areas with relatively easy access to hydrothermal energy will continue to be an important source of energy, it is the areas of "normal" temperatures where the future of geothermal energy lies.

There are two basic forms of geothermal energy. One is the indirect form which uses heat extracted from rocks encountered deep below the ground surface to generate electricity. These systems go by a variety of names including "hot rocks" or "enhanced geothermal systems". The other is the direct form which uses the ground within a few tens of metres of the surface as a heat source in winter and sink in summer for heating and cooling domestic, commercial and industrial buildings.

## **2 Enhanced Geothermal Systems (EGS) for Power Generation**

Within about 5-10m depth from the ground surface, the temperature is strongly influenced by the atmospheric temperature, and temperature variations due to daily or seasonal effects can be large. With increasing depth and down to several tens of metres below the surface, the temperature becomes relatively constant and is initially close to the mean atmospheric temperature for any particular location. Therefore, the ground is warmer than the atmosphere during winter and cooler during summer, a generalisation that applies for most locations around the world regardless of geology.

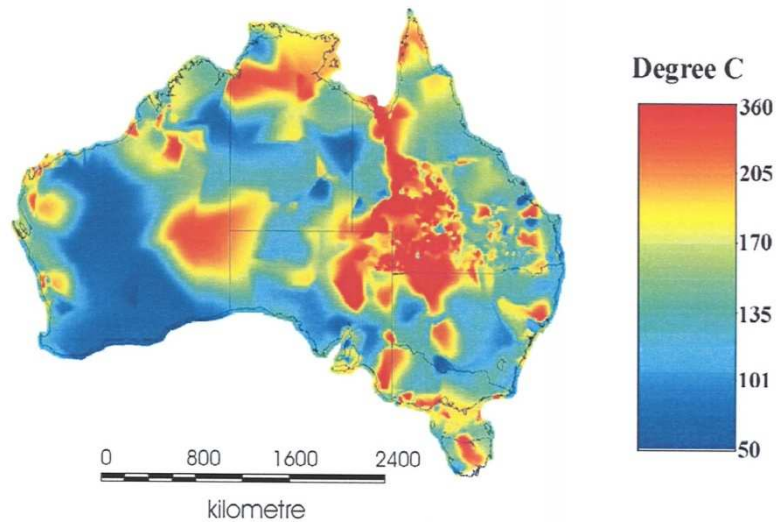
Below this relatively thin surface layer, for regions not influenced by volcanic activity, the average thermal gradient is about 25°C to 30°C increase per kilometre, due to heat flux from within the Earth. However, there are many areas where a much higher gradient has been recorded. These areas typically have at least one of the two important characteristics:

- there is significant presence of radiogenic decay, and
- there are thick highly insulating surface formations which reduce heat loss to the atmosphere.

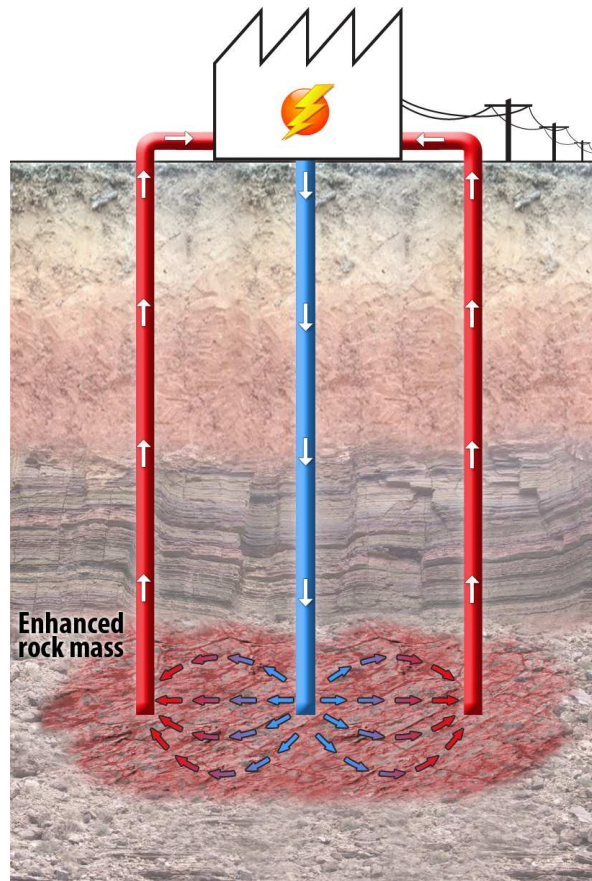
Figure 1 shows a map of Australia indicating the estimated temperatures at 5km depth. To the east of the central part of the country there is a large region where the estimated temperatures are around 250°C or more. The high temperature gradient for this region far from a tectonic plate boundary is due to high levels of radiogenic activity buried beneath thick, insulating sediments.

Clearly, the greater the temperature gradient, the shallower the boreholes required to reach temperatures which can provide enough heat for commercial power generation. In very broad terms, the minimum temperature at depth which can be used to produce electrical power at the surface is about 150 °C. However, much more efficient systems may be developed with greater temperature, preferably significantly greater than 200°C.

The basic EGS comprises an injection well to depths of about 4 to 5 kms, an "enhanced" rock mass extending out from the well, a production well and a power station at the surface. Water is forced down the injection well, through the hot fractured rock mass to pick up heat and then returned to the surface via the production well. This hot water is then used to produce steam or another more volatile gas to drive turbines to produce electricity. Figure 2 shows a schematic view of an EGS project.



**Fig. 1:** Estimated temperatures at 5km depth in Australia (Sommerville et al. 1994)



**Fig. 2:** Schematic view of an EGS project

The cost of drilling the injection and production wells is considerable, and would typically be of the order of \$20 million to \$30 million for the pair. As well drilling can often account for over 50% of the total cost of an installation, any advances in this area would have a significant impact on total costs. Areas of the technology which are advancing include the use of expandable casing, drilling with casing, more efficient under-reaming techniques to increase borehole diameter, use of more thermo-chemical resistant cements in casing, and probably most importantly, increases in the rate of

drilling penetration. This latter factor is the subject of intense research by a number of organisations so that drilling bit life and effectiveness can be improved.

One of the critical steps in any EGS project is the effective enhancement of the rock mass reservoir to make it adequately permeable for economic and sustainable production. This is achieved by packing off the injection well at the target depth and increasing the fluid pressure between packers until the natural fractures in the rock mass open. By controlling the volume and pressure of injected fluid, the permeability will increase and extend out from the well. The fractures propagate in a direction which is controlled by many interacting factors and which can often vary considerably in extent and direction. The hydraulic pressures tend to cause a shearing movement of the fractures leading to small permanent shear displacements of the rough opposing faces of a fracture. As these rough surfaces do not match, the surfaces tend to stay propped open on the many individual asperities on each fracture surface, thereby “locking in” a much higher permeability. It is also common practice to introduce some sand into the fluid which enters the fractures and performs the same propping action.

The water pressures are maintained so the extent of the enhanced reservoir increases to the dimensions required for production. A key part of the enhancement phase is the monitoring of the fracture development by means of acoustic emission measurement. These geophysical techniques allow the many micro-seismic events that occur when the fractures develop to be mapped so that the volume of rock enhanced can be estimated. Once these have been completed, it is then necessary to decide the best location for the production well.

There are many factors which have to be considered, measured and assessed for any one EGS. The most critical are the temperature and volume of the fluid that can be delivered. It is vitally important that the injected fluid can pass from the injection well to the production well adequately quickly so that there is a sufficient volume of hot water. This is clearly related to the permeability and length of flow paths within the rock fracture zone. However, it is also important that the fluid has an adequately long residency time in the hot rock to absorb the heat. Problems arise when the rock becomes too permeable and there is short circuiting between the injection and production wells, so that relatively large volumes of fluid can be delivered but without an adequate level of temperature. Clearly there is a balance that must be achieved between flow rate and heat gain. As a general guide, flow rates need to be in the range of about 30 to 100 kg of water per second with the lower rate applicable to temperatures well in excess of 200°C while the higher rate is applicable to temperatures approaching the current lowest practical temperature of about 150°C.

A vitally important factor for any EGS is its effectiveness over time. For example, depending on the size of the reservoir and its rate of heat replenishment, it is possible to draw the operating temperature of the reservoir down to the extent that it cannot provide water at an acceptable commercial temperature. This may require operations to be slowed down or possibly stopped until there has been adequate recovery. Another major factor involves the fluid flowing through the fractures causing some of the rock to dissolve thereby increasing permeability. While some increase may be acceptable, indeed advantageous, there could become a point at which the flow becomes unsatisfactory. Alternatively, there may be scaling and deposition within the fractures which has the opposite effect of reducing permeability to the extent that the volume yield of water is inadequate. These effects also need careful consideration and understanding. While there are a number of remedial techniques currently under investigation, it is clear that we must develop a detailed understanding of these effects and develop an armoury of methods to ensure long serving reservoirs.

It is clear from the above that there are many factors which can influence the effectiveness of an EGS. Indeed, for the risks associated with an EGS to be adequately reduced so that it can become a commercial reality, we must develop reliable tools to allow us to predict the performance of a reservoir over time. There are many modelling techniques currently being developed which consider the different variables (including fracture network distribution and character, in-situ stress field, response of fracture network to hydraulic pressures, relationship between aperture and permeability,

and, of course a number of micro and macro geological features). These then need to be calibrated and validated against the increasing amount of field data that has and is being collected from test locations such as Fenton Hill and Desert Peak (USA), Rosemanowes (UK), Hijiori (Japan), Soultz (France), Landau (Germany), Basel (Switzerland) and the Cooper Basin (Australia).

The production of electricity from geothermal energy involves the removal of hot water from the ground and the conversion of its heat energy to electrical energy. Once the heat is removed, the water is returned to the ground for reheating. As discussed earlier, as it generally appears that the supply of heat from the earth more than balances the heat removed, the system is totally renewable and sustainable. The only part of an EGS that is visible is the power station at the surface and the distribution lines, the rest is underground. There are virtually no greenhouse gases, or other emissions, no major intrusions into the ground surface or waste to be removed and stored.

The one significant environmental issue that does need serious consideration is that when an EGS reservoir is enhanced, the micro-seismic events involved with the fractures opening are in fact small earthquakes. They are the events which are monitored as acoustic emissions to determine the extent of the enhanced reservoir. It follows that seismicity is expected to occur and has been routinely monitored in most EGS sites. For example, in the Cooper Basin in Central Australia, the largest earthquake measured was about magnitude 3.7. However, this region is in the centre of a large seismically inactive continent with very little locally that could experience any damage.

The situation in Basel, Switzerland, however, is very different. A commercial EGS project was commenced in the late 90s. An injection well was drilled to a depth of about 5kms and enhancement commenced at the beginning of December 2006. Almost immediately there was a pronounced increase in seismic activity and an event of magnitude 2.7 was recorded after about 5 days of enhancement. The process was stopped but the seismic events continued for many months. The largest shock was about magnitude 3.4 which occurred a few hours after stopping the enhancement. Slight non-structural damage was reported to have occurred in numerous buildings (usually some fine cracks in plaster walls) and about US\$7 million was paid out in insurance claims. It should be pointed out that according to Kraft et al. (2009), the insurance settlements were probably very generous with the damage significantly overstated. Also, events of the magnitudes recorded, although not to be ignored, must not be confused with those highly destructive earthquakes of considerable greater magnitude that regrettably occur from time to time. What must be made clear is that the good citizens of Basel had a good reason for being concerned because the city is located on an active fault. In 1356, with an event of magnitude 6.5, a significant part of the city was destroyed. The lesson which must be learnt here is that a thorough risk assessment must be undertaken with any planned EGS project so that the risk can be rationally rather than emotionally evaluated.

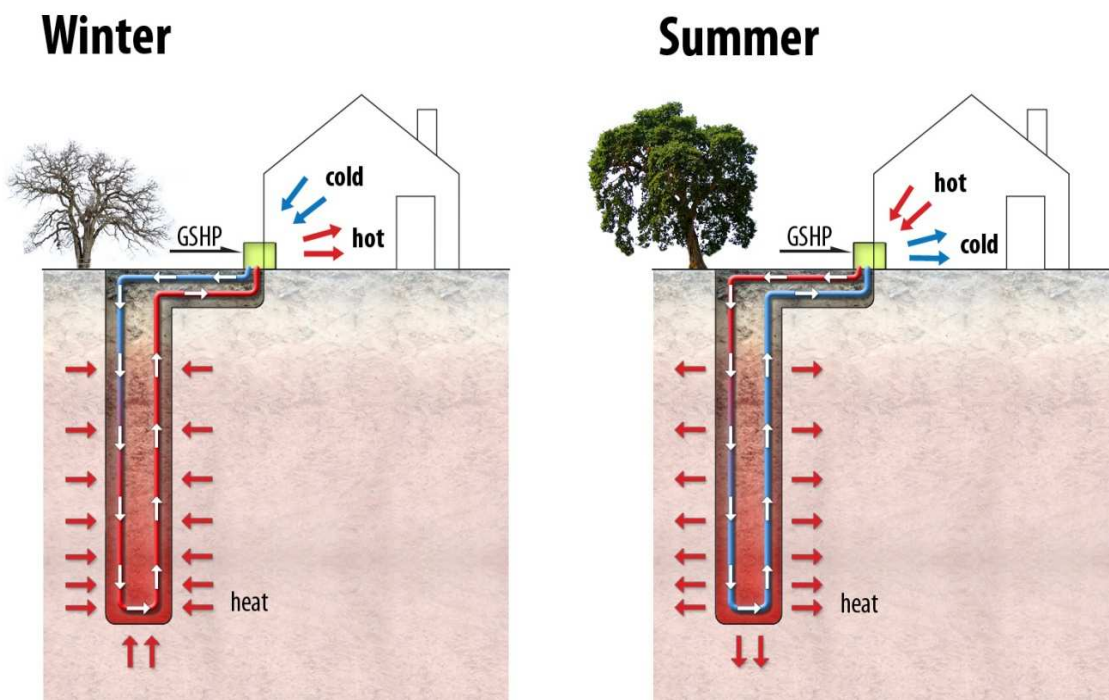
At this point in time, there has been no commercially demonstrated example of EGS generated electricity. However, there are many organisations around the world which are close to this important breakthrough in geothermal technology, most notably in Australia, Europe and USA.

The most comprehensive summary of the many issues involved with EGS is probably the MIT (2006) report, although the recent Stanford Geothermal Workshop (Stanford University 2010) and the 2010 World Geothermal Congress in Bali (International Geothermal Association 2010) provide specialist papers dealing with a range of issues.

### **3 Direct Geothermal Systems**

The other form of geothermal energy is the direct form which uses the ground within a few tens of metres of the surface as a heat source in winter and sink in summer for heating and cooling domestic, commercial and industrial buildings. This highly cost and energy efficient technique is growing rapidly in Europe and North America, but is only just starting to generate interest in other parts of the world. Excellent overviews of these systems may be found in Brandl (2006), Banks (2008) and Preene and Powrie (2009).

Each direct system involves the circulation of fluid (water or refrigerant) through pipes built into building foundations, or in specifically drilled boreholes or trenches, and back to the surface. In heating mode, heat contained in the circulating fluid is extracted by a ground source heat pump (GSHP) and used to heat the building. The cooled fluid is reinjected into the ground loops to heat up again to complete the cycle. In cooling mode, the system is reversed with heat taken out of the building transferred to the fluid which is injected underground to dump the extra heat to the ground. The cooled fluid then returns to the heat pump to receive more heat from the building. Depending on several factors, about 100m to 150m of buried small diameter pipe can continuously provide for most heating and cooling requirements for the average family home. The length of pipe is usually accommodated by a number of vertical boreholes to around 50m deep, although deeper boreholes are commonly used. Fig. 3 shows a schematic view of such a system in which the ground loop system (GLS) is connected to the structure's conventional heating and cooling system via a GSHP. Note that this drawing is not to scale and the borehole would only be up to about 150mm in diameter.

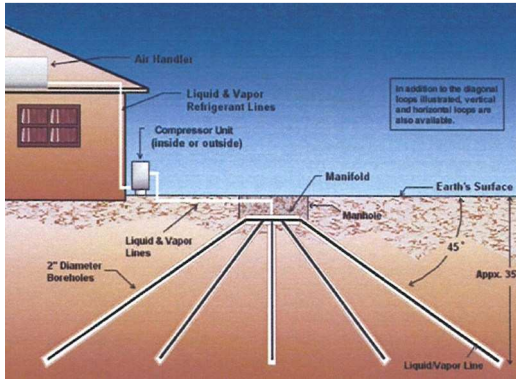


**Fig. 3:** Schematic view of a direct heating and cooling system (borehole not to scale).

The cost of direct geothermal heating and cooling systems for larger buildings can be reduced by incorporating pipe into their generally larger and deeper foundations, instead of the relatively expensive drilling of separate boreholes.

Figs. 4 to 9 show a number of configurations of GLSs. The installations in Figs 4, 5 and 6 would be appropriate for relatively small buildings whereas the installations shown in Figs 7, 8 and 9 would be appropriate for larger multistorey buildings.





**Fig. 4:** Possible GLS configuration for a house (Direct Energy, 2010).



**Fig. 5:** Installation of copper ground loop into small diameter borehole (Payne, 2010).



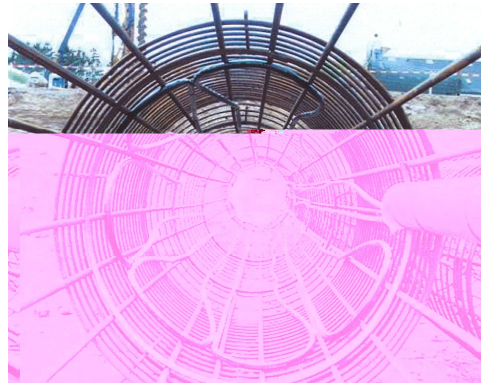
**Fig. 6:** Shallow horizontal "slinky" ground loops in trenches (Banks, 2008).



**Fig. 7:** Lowering HDPE ground loops into the ground on the reinforcing cage of a section of diaphragm wall (Enercret, 2009).



**Fig. 8:** Horizontal ground loops in a mass concrete base slab (Enercret, 2009).



**Fig. 9:** HDPE ground loops in reinforcing cage of a large diameter pile before vertical installation (Enercret, 2009).

These systems can operate continuously (which wind and solar systems do not), they are relatively maintenance free over a long period of time and their costs are modest with capital expenditure recovered rapidly. There are several buildings in Europe which are supplied by well over 1.5MW of heating and cooling. They provide a very effective means of significantly reducing the carbon footprint of any building.

The two key elements of any system are the GSHP and the GLS. The GSHP is, in effect, a powerful domestic refrigerator which is capable of taking heat out of one area and delivering it to another. Therefore, when working in one mode, it takes heat out of the fluid in the GLS and delivers it to a building to be heated. When switched to the cooling mode, it takes heat out of the building and

delivers it to the GLS for disposal to the ground. The operational characteristics of a GSHP are clearly linked to the performance characteristics of the GLS. GSHPs typically operate with a coefficient of performance (COP) of around 4. This means that for every 1kW of electricity used to power the heat pump, 4kW of thermal energy is produced. A slightly smaller energy advantage is obtained when operating in the cooling mode. This represents a considerable saving in power consumption (and thus the need for its generation) for heating and cooling.

Vertical or near vertical GLSs generally extend to depths well below the zone of influence of the surface air temperature. As noted above, this depth is generally about 5 to 10m below the surface where the ground temperature is effectively the same as the weighted mean annual air temperature. This is about 15°C for Melbourne, with Tasmanian temperatures a few degrees lower and Queensland temperatures generally getting above 20°C. GLSs extending well into this zone of virtually constant temperature are more efficient than GLSs placed closer to the surface where temperatures vary according to the season (and within about a metre of the surface additionally according to the time of day). The near surface GLSs are generally installed in horizontal trenches or within structural ground slabs (see Figs 6 and 8). The reason for the lower efficiency of near surface horizontal GLSs is that these shallower regions will be cooler in winter when heat is required and warmer in summer when heat needs to be dumped. However, as it is generally much cheaper to place GLSs in locations closer to the surface than at greater depth, a trade off with a greater length of shallow GLS to allow for a lower efficiency may often provide a more effective overall economic balance.

As is indicated in Figs 4 to 9, GLSs can have many configurations with the energy output dependent on many factors including the type of ground involved, materials used, the installation geometry and the fluid flow rates. While it is possible to broadly estimate the energy delivered on the basis of these variables, current technology only allows a very approximate estimate which could include large variations and inaccuracies. This is not a satisfactory situation as installations could be significantly under- or over-designed, leading to systems which are neither cost effective nor competitive. There is clearly a need for more accurate design measures. The reason for the approximate nature of the performance predictions is primarily because direct geothermal applications up until recently have been driven by the heating, ventilation and air conditioning (HVAC) industry whose main concern has been with the above ground technology. It is only recently that the importance of the below ground GLS component of the overall technology has been seen as requiring significant research.

It follows that in order to develop comprehensive design data, considerably more research is required into the performance of GLSs. There is a need for answers to questions such as: i) how do different ground conditions influence the overall energy output, ii) what effect is there with different geometrical system configurations, iii) how does the pipe spacing and the materials used for the different components within the ground affect overall performance, iv) how does energy output and performance vary with fluid flow rates (laminar vs turbulent) and different fluids (water vs refrigerants vs mixtures).

#### **4 Concluding Comments**

EGS and direct geothermal heating and cooling using GSHPs are new and emerging technologies that have the potential to significantly reduce the world's dependence on carbon based energy sources. The technologies are complementary: EGS has the potential to significantly increase supply of "clean" electricity and GSHPs the potential to reduce demand. Furthermore, and unlike the better known forms of sustainable energy, geothermal energy is available 24 hours a day, 7 days a week.

Commercial application of EGS technology is some years into the future but its enormous potential demands investment for further research. Direct geothermal energy and ground source heat pump technology is available now – policy makers, the construction industry and the public need to be educated and the potential of these systems demonstrated. Research should focus on optimising ground loop and GSHP systems to maximise economic, as well as environmental, benefits.



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